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Feasibility assessment of poplar bioenergy systems in the Southern Europe

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Abstract

A detailed reliability assessment of bioenergy production systems based on poplar cultivation was made. The aim of this assessment was to demonstrate the Economic feasibility of implementing poplar biomass production for power generation in Spain. The assessment considers the following chain of energy generation: cultivation and harvesting, and transportation and electricity generation in biomass power plants (10, 25 and 50 MW). Twelve scenarios were analysed in accordance with the following: two harvesting methods (high density packed stems and chip production in the field), two crop distributions around the power plant and three power plant sizes. The results show that the cost of biomass delivered at power plant ranges from 18.65 to 23.96 € Mg^{-1} dry basis. According to power plant size, net profits range from 3 to 22 million -€ per yr.

Sensibility analyses applied to capital cost at the power plant and to biomass production in the field demonstrate that they do not affect the feasibility of these systems. Reliability is improved if benefits through selling CO_2 emission credits are taken into account.

This study clears up the Economic uncertainty of poplar biomass energy systems that already has been accepted as environmentally friendlier and as offering better energetic performance.
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Keywords: Energy crops; Supply chain; Power plant; Final biomass cost

Contents

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1. Introduction

Interest in the production of biomass by means of energy crops has increased over the last 40 years in Europe. Northern and Central European countries began to promote energy crops after the oil crises of the mid-1970s mainly in an attempt to counteract escalating prices [1,2]. Southern European countries such as Spain did not pay appropriate attention to the endeavour to produce additional renewable sources [2]. Currently, the promotion of biomass as a renewable energy is an important target for European policies, being incorporated within national policies [3–5]. Biomass-based electricity is promoted in the Renewable Electricity Directive, which aims to increase the use of renewable energy sources to 22% by 2010 [4]. Spain, in common with many other countries in the European Union, does not have great reserves of petroleum or natural gas, and therefore needs to import around 75% of the total energy demand [6]. Biomass produced as energy crops on a national scale can be an opportunity to reduce external energy dependency.

The biomass from energy crops as a renewable energy source is seen as a significant contributor to the carbon dioxide abatement strategy aiming at an 8% reduction in Europe, as required by the Kyoto protocol. Within the European objective, Spain has been requested not to increase more than 15% over the 1990 emission levels by 2012 [7–10].

Some of the energy crops analysed in experimental and demonstration parcels for their implementation in Mediterranean areas are annual species such as Ethiopian mustard (*Brassica carinata*) [11,12], cardoon (*Cynara cardunculus*) [13,14], sweet sorghum (*Sorghum bicolor* L.) [14,15] as well as short rotation coppices (SRC) such as poplar (*Populus* sp.) [16] or eucalyptus (*Eucalyptus globulus*) [17].

In accordance with the national Renewable Energy Plan, biomass must contribute 29.67% to the total renewable energy production for the year 2010 [5]. Energy crops are seen in the Spanish plan as a significant part of the strategy to achieve the expected energy objectives (3.35 Mtep) [5,18].

The poplar crop has been selected in this study because of its friendlier overall environmental performance and its high biomass production yields per hectare in Mediterranean areas [3]. An environmental disadvantage of this crop is its high consumption of water, which is a limited resource in Spain and other Mediterranean countries [19]. Given this limitation, the implementation of poplars as an energy crop competes with other crops in areas having sufficient water and land availability [20]. Currently in Spain, these areas are extensively occupied by woody crops aiming to produce wood for the paper and packaging industries. Additionally the implementation of this crop in unexploited marginal areas is also under consideration [21].

In this context, the main aim of this study is to examine the economic viability of the production of energy by means of biomass produced in poplar energy crops. The feasibility study also takes into account the marginal benefit of CO_2 emission reduction when substituting fossil fuel.

2. Methodology

2.1. The poplar bioenergy system analysed

The feasibility study analyses the three main subsystems of energy production with poplar biomass in Spain: (a) poplar cultivation and harvesting, (b) transport and (c) energy conversion. Poplar cultivation stages cover a 16-year period, including three 5-year rotations. The best period considered for

Table 1
Poplar field labours timeline

Year	Activity
0	Plow, base fertilisation, herbicide, plant, first cut
1, 6, 7and 11,12	Herbicide or insecticide application or no labour
2, 8 and 13	Top fertilisation (during the first cycle) or base fertilisation (during the rest)
3, 9 and 14	No labour (during the first cycle) or top fertilisation (during the rest)
4, 10 and 15	No labours
5, 11 and 16	Biomass harvest and elimination of the poplar stools during the last cycle

harvesting is during the autumn and winter, when leaves have fallen. This improves both the handling of poplar biomass and the efficiency of the harvesting operation [22]. Table 1 shows the agricultural labour covered throughout the entire cycle of the poplar crop. Water irrigation and the associated energy consumption are not included in the analysis.

Poplar biomass has an initial moisture content of about 50% at harvesting. Two alternatives for harvesting were analysed: production of high-density packed stems and chip production. In the case of packed stem production, biomass fuel is left in the field to reduce water content to 20% through natural drying. Stems stored in the field are then transported to the power plant and chipped regularly according to the normal delivery schedule over the working period of the plant (333 days yr^{-1}).

As regards the option of chip production, the poplar is immediately chipped in the harvesting period (150 days yr^{-1}) [23] and is then directly transferred to the power plant for storage. A moisture content reduction has to be achieved at the plant, to about 20%, for better combustion.

In both cases, poplar biomass is assumed to be transferred by truck from the field to the combustion plant, applying the load limit authorized in Spain. Transport and disposal of ashes produced in the bioenergy conversion plant are included as a part of the system under study (Fig. 1).

Table 2
Poplar biomass base case scenarios definitions

Scenario	Biomass transported	Power (MW)	*Pr* (Mg ha^{-1} yr^{-1})	Crop distribution area (Cd) (%)
Sc. 1	Stems	10	13.5	90
Sc. 2	Stems	10	13.5	10
Sc. 3	Stems	25	13.5	90
Sc. 4	Stems	25	13.5	10
Sc. 5	Stems	50	13.5	90
Sc. 6	Stems	50	13.5	10
Sc. 7	Chips	10	13.5	90
Sc. 8	Chips	10	13.5	10
Sc. 9	Chips	25	13.5	90
Sc. 10	Chips	25	13.5	10
Sc. 11	Chips	50	13.5	90
Sc. 12	Chips	50	13.5	10

2.1.1. *Scenarios analysed*

Twelve scenarios are defined for the economic poplar feasibility study. These assume an average poplar production of 13.5 tonnes of dry matter, and include travel distance according to the occupancy of cropping area (Cd) area around the power plant. These scenarios are detailed in Table 2.

2.2. *Supply and logistical aspects for the poplar bioenergy system*

Biomass required for the power plant, land-crop surface required to produce this quantity of poplar biomass and the logistical needs expressed in number of trucks required to transfer the biomass are calculated to determine the effect on the economic performance of the system.

2.2.1. *Poplar biomass required as a fuel for a bioenergy conversion plant*

Annual biomass requirements (BF) for biomass power plants are calculated taking into account the poplar's low heating value (LHV) [18.2 MJ kg^{-1} (d.b.)] [24], the number of operation hours over a year (8000 h) and plant efficiency (25, 28 and 30% for 10, 25 and 50 MW,

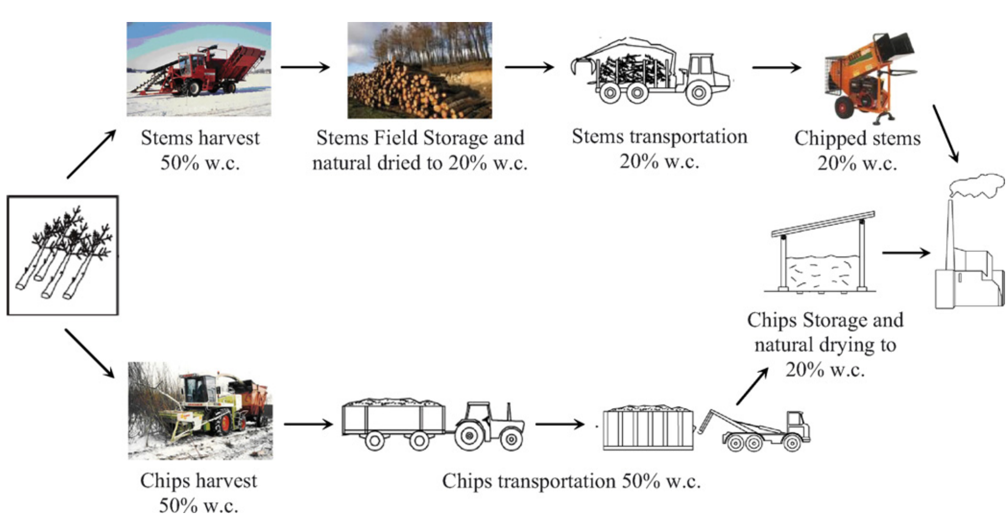

Fig. 1. Scheme of the system under study.

Table 3
Poplar biomass supply for each plant

Power (MW)	Poplar requirement (Mg d.b.)	Poplar requirement (Mg 20% w.c.)
10	63,297	79,120
25	141,287	176,610
50	263,737	329,671

respectively) [25]. Supply requirements for each plant are detailed in Table 3.

2.2.2. *Cropping area required by a biomass power plant and transport distance*

Considering the annual biomass fuel requirement BF (Mg) for a 10, 25 and 50 MW biomass power plant, the cropping area needed to supply a power plant CA (ha) is calculated through cropping productivity Pr (Mg ha^{-1} yr^{-1}). See the following expression:

$$\mathrm{CA} = \mathrm{BF}\,Pr^{-1} \tag{2}$$

A poplar production yield variation of between 9 and 20 Mg (d.b.) ha^{-1} yr^{-1} was considered and a value of 13.5 Mg (d.b.) ha^{-1} yr^{-1} (see Table 2) was assumed as average in the present study.

The area cultivated has a direct influence on the total distance of transport. Medium transport ratio to be appealed by biomass fuel supplier trucks D (km) is estimated, as follows:

$$D = \left(\frac{\mathrm{CA}}{2\pi\,\mathrm{Cd}\,100}\right)^{0.5} \tag{3}$$

where CA is the cultivation area, Cd is crop distribution area and π.

2.2.3. *Number of trucks required for biomass poplar transportation*

Number of trucks needed daily to supply a biomass power plant is defined from the total biomass fuel required for the power plant, the daily number of trips made by a truck and the daily biomass transported by a truck.

Table 4 shows the number of trips made by a 16 Mg truck per day, from the field to the power plant considering legal speed limits for a 16 Mg truck, loading and unloading time for poplar packed stems (high density) and chips, travel time by road and traffic incidents time. Trips per day made by a truck (e) were calculated by means of the truck driver's labour journey time (8 h per day) divided by total travel time.

The poplar biomass transported daily by a truck was calculated according to the maximum weight and volume of a load per truck (16 Mg legal practical load for a Spanish regional transport truck) [26].

For a biomass density value higher than 340 kg m^{-3}, load weight becomes a limiting factor in transport. On the other hand, for density values lower than these, the volume of biomass limits transport load.

Table 4
Travels per day made by a truck transporting stems and chips from the field to the power plant

Distance from field to power plant (km)	(a) Going and return time by road (h)		(b) Loading time for a truck (h)		(c) Unloading time at plant (h)		(d) Transport time lost by traffic (h)		Total time by travel (e) = (a) + (b) + (c) + (d)		Travels per day made by a truck (Tpd)	
	Stem	Chip	Stem	Chip	Stem	Chip	Stem	Chip	Stem	Chip	Stem	Chip
1–5	0.16		0.8	0.16	0.33	0.16	0.16	0.16	1.45	0.64	5.5	12.5
5–10	0.33								1.62	0.81	5	9.5
10–20	0.58								1.87	1.06	4.5	7.5
20–30	0.83								2.12	1.31	4	6

Table 5
Trucks needed to supply biomass fuel to a power plant and total transport distance

	Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5	Sc. 6	Sc. 7	Sc. 8	Sc. 9	Sc. 10	Sc. 11	Sc. 12
Quantity of biomass transported per day (Mg)	238	238	530	530	990	990	844	844	1,884	1,884	3,516	3,516
Trucks acquired to transport poplar biomass	3	4	7	8	14	15	7	9	14	19	34	43

The assumed high density packed stem density is 310 kg m^{-3} (20% w.c.), while harvested chip density is 280 kg (50% w.c.) m^{-3}.

Furthermore, the different intensity of transport necessities for both biomass fuels (stems and chips) were considered in order to calculate the total number of required trucks.

Table 5 shows trucks needed to supply power plants as considered over a year for each scenario.

2.3. Cost and benefit analysis

2.3.1. Poplar cultivation and harvesting

Biomass-cultivation cost includes investment, depreciation and operational costs (the total cost for the agricultural machinery), agrochemical acquisition and use and maintenance of agricultural parcels, all of which influences the total cost of cultivation and harvesting [27].

2.3.1.1. Total cost of agricultural machinery. Total cost of agricultural machinery (TCAM) considers the fixed costs (FCH) and variable cost per hectare (VCH). FCH include depreciation with an interest rate of 4.75% [28], and all insurance.

VCH includes fuel consumption by agricultural tractors and harvest as well as lubricants, grease, replacement of parts, repairs and maintenance. Table 6 shows the value of the components taken into account over the economic assessment of the agricultural subsystem.

Table 6
Economical values used to calculate the fixed and variables cost during the cultivation and harvesting subsystem

Component	Cost
Fixed cost parameters	
Tractor investment [27]	71,560 €
Harvest investment (stems) [29]	216,216 €
Harvest investment (chips) [29]	225,225 €
Re-sell price of machinery [27]	15% P
Machinery lifetime in hours [27]	12,000 h
Variable cost parameters	
Diesel Agricultural Spanish price 2006 [30]	0.67 € l^{-1}
Diesel consumption	316–330 l ha^{-1}
Oil lubricant proportion cost respect diesel [27]	4.50%
Grease lubricant proportion cost respect diesel [27]	10%
Machinery material life time (replacement) [27]	2500 h
Pneumatic cost [27]	3.364 €
Repairs and maintenance [27]	85% of the acquisition price of machinery
Labour cost [27]	14.43 € h^{-1}

Where possible, the use of common agricultural equipment is assumed (e.g., a tractor). For prototype equipment, information from the literature is used. Large machines are assumed to be operated by contractors because the machines are usually too expensive for one farmer only. To enable a relevant comparison, cost calculations of machines that can only be used for poplars are based on full utilization.

2.3.2. Transportation cost

Economic evaluation of poplar transport to the power plant was based on:

- Investment related to trucks and loading systems;
- Maintenance and reparation costs related to trucks;
- Operating costs related to labour cost and diesel consumption.

In order to model the long-term costs for transport machinery, contractor costs based on prices from [31,32] were used. Labour cost was assigned from the bibliography [27,29]. Input data used to describe transportation cost are shown in Table 7.

2.3.3. Operating cost calculation for transport at power plant site

Assuming both the same number of truck drivers as the daily trucks used to supply the power plant and driver salary (Table 7), labour cost was calculated according to the transportation periods.

Diesel cost by trucks is directly calculated from the distance needed to be covered between the biomass power plant and the cultivations, number of trips made by a truck during the transportation period and the trucks needed daily to supply the power plant. In addition, a diesel consumption of 0.335 l km^{-1} [33] and a Spanish diesel cost of 0.9751 € l^{-1} were assumed, based on the average cost for 2006 [34].

2.4. Chipping cost at plant

When biomass in the form of stems arrives at the plant, the chipping process has to be made in order to introduce the biomass to the boiler. Assumed chipping cost at the power plant is 2.83 € Mg^{-1} Poplar stems [29].

2.5. Ash transportation and disposal cost

Ash transportation and disposal cost was calculated from the quantity of ash generated per Mg of biomass burned at the plant

Table 7
Components of total transport cost evaluation

Component	Factor	Cost (€/truck)
Truck investment (chips transport)	Ic	70,000 [31]
Truck investment (stems transport)*	Is	98,000 [31]
Truck driver labour cost (chips transport)	Lc	21,080 yr^{-1} [31]
Truck driver labour cost (stems transport)	Ls	25,960 yr^{-1} [31,32]
Annual maintenance and reparation cost (chips transport)	Mc	0.5 Ic $lifetime^{-1}$ (7 yr) [32]
Annual maintenance and reparation cost (stems transport)	Ms	0.5 Is $lifetime^{-1}$ (7 yr) [32]

* Crane arm investment for stems loading operation on the truck is included.

(0.02 Mg of ash × Mg biomass $burned^{-1}$) [35]. These costs include total transportation costs for the ash generated, assuming a distance of 25 km and disposal taxes in Catalan landfills (72 € Mg^{-1}).

2.6. Power plant

Power plant costs of 10, 25 and 50 MW were analysed with the purpose of obtaining economic reliability using poplar as a biomass fuel.

2.6.1. Power plant investments

A range of investments for each power plant was considered as generalisable to the Spanish case, selecting average data to obtain an approximation of realistic economic values. Fig. 2 shows investment data range considered to the economic study. Expression (4) shows a mathematical correlation between power and the investment carried out (€ kWe^{-1} yr^{-1}):

$$\text{Biomass power plant capital cost} = 5217\,\text{MW}^{0.2946} \tag{4}$$

Table 8
Number of workers and labour cost at 10, 25 and 50 MW biomass power plant

Power plant (MW)	Plant workers
10	8
25	12
50	19

2.6.2. Plant maintenance and operating costs

Plant maintenance costs was calculated as 1.5% of total plant investment according to the bibliography [25]. Table 8 shows the number of plant workers considered in order to estimate power plant operating costs [24,25]. Insurance and other minor plant costs were calculated as 1% of total plant investment [25].

2.7. Annual benefits and economic feasibility indicators used

Annual benefits earned were calculated according to the current electric tariffs for biomass energy plants, as established by Spanish Royal Decree 661/2007 [42].

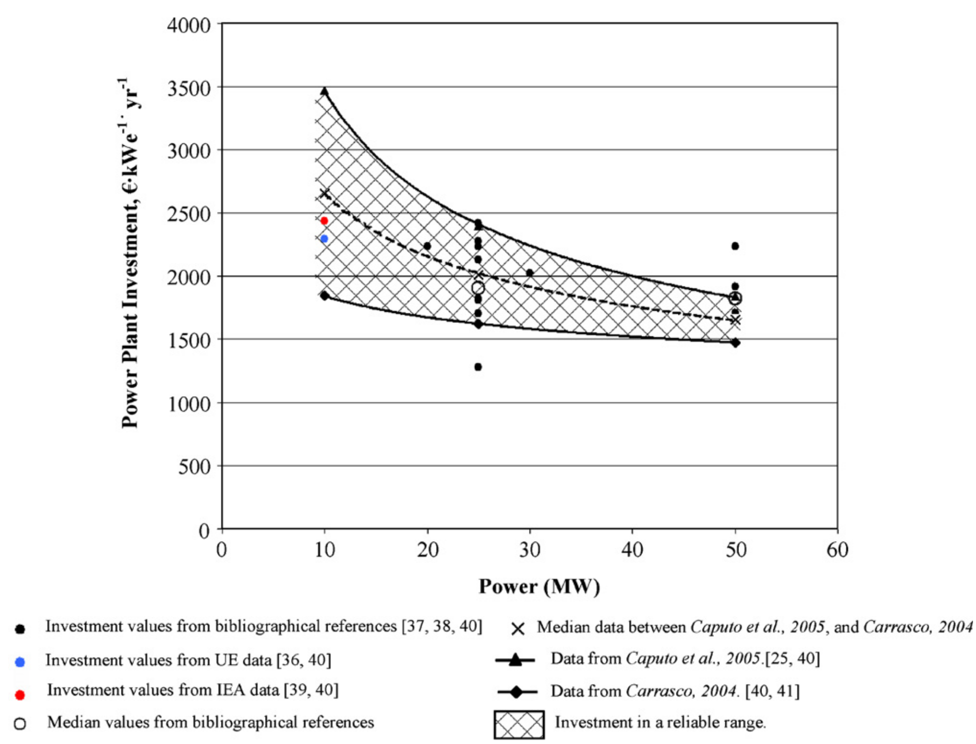

Fig. 2. Biomass power plant investments, data considered in the study [25,36–41].

Table 9
Poplar production and harvesting biomass tonne cost (€ Mg^{-1} yr^{-1})

	Biomass production (Mg d.b. ha^{-1} yr^{-1})							
	9.00		13.50		15.00		20.00	
	Stems	Chips	Stems	Chips	Stems	Chips	Stems	Chips
Total machinery cost								
Fixed costs	3.89	4.98	2.79	3.32	2.33	2.99	1.75	2.24
Variable costs	2.15	2.33	1.43	1.55	1.29	1.40	0.97	1.05
Labour cost	2.41	3.06	1.81	2.04	1.45	1.84	1.09	1.38
Agrochemicals acquisition	7.85	7.85	5.24	5.24	4.71	4.71	3.53	3.53
Use and maintenance of the parcel	4.98	4.98	3.32	3.32	2.99	2.99	2.24	2.24
Total cost production	**21.89**	**23.22**	**14.59**	**15.48**	**12.77**	**13.93**	**9.58**	**10.45**

To define the economic feasibility for each scenario, economic indicators such as simple payback period (SPP), net present value (NPV) and internal rate of return (IRR) were used. An interest rate of 4.75% [28] and a 20-year period were considered for NPV calculation.

2.8. Sensibility analysis

Three independent sensibility analyses were carried out using the following variables: investment cost, CO_2 benefits from selling emissions credits and biomass crop yield.

A plant investment cost variation of 10% was studied and a CO_2 price range per Mg from 5 to 50 € Mg $CO_2{}^{-1}$ with a CO_2 generating factor from coal (0.95 Mg CO_2 MWh^{-1}) [9] was analysed. Finally, new economic feasibility rates were calculated, taking into account crop-yield variation from 9 to 20 Mg (d.b.) ha^{-1}.

3. Results

3.1. Biomass production and harvesting cost

The total cost production for poplar biomass reached 3.065 or 3.342 € ha^{-1} over the 16 crop years depending on whether biomass was harvested in stems or chips. This implies a yearly production cost of poplar biomass of 197 € ha^{-1} yr^{-1} when the poplar is harvested as stems and 209 € ha^{-1} yr^{-1} when harvested as chips. Biomass production cost will vary according to total biomass production obtained during the different harvesting periods. Table 9 shows the variability of poplar biomass cost/tonne according to the different biomass productions and harvesting methods considered.

In the case of poplar stems, the cost of dry biomass production per tonne and of harvesting oscillates from 9.58 to 21.89 € Mg^{-1} d.b. yr^{-1} depending on the total biomass production obtained per hectare. For chip production, the maximum cost obtained is 23.22 € Mg^{-1} d.b. yr^{-1} with a minimum of 10.45 € Mg^{-1} d.b. yr^{-1}.

These ranges are comparable with the values obtained in other studies that analyse the cost production and harvest for short rotation crops aimed at biomass production. In these studies the specie selected was willow. The biomass cost in the field after harvesting was 13.88 € Mg^{-1} d.b. for stem production and 14.76 € Mg^{-1} d.b. for chip production. Both cases consider an average biomass production of 8–12 tonnes dry matter with an overall cultivation period of 20 years [29]. According to other studies where poplar is cultivated for 8 years [43], poplar biomass cost is 56 € Mg^{-1} d.b. The main reason for this variability is the total cultivation period of the crop under exploitation. When short rotation crops are cultivated over large periods (16–20 years), the final biomass cost is less in comparison with shorter rotation times.

Chip production in the field has higher costs compared with stem production due to fixed and variable costs for major machinery as well as to the higher labour costs involved.

For both biomass types (stem and chip), the agrochemical acquisition and parcel-land rent are the main cost that the farmer has to assume. Both represent between 55.31% and 60.31% of the total biomass production cost.

When total cropping cost is grouped in periods, the results obtained show that the most expensive period is the crop implementation year. The two next most expensive periods are the second and third rotation. First rotation and land-restoration work are the lowest cost periods for labour. In contrast, parcel-rent cost is one of the most expensive costs that the farmer has to face in the conditions studied (see Fig. 3).

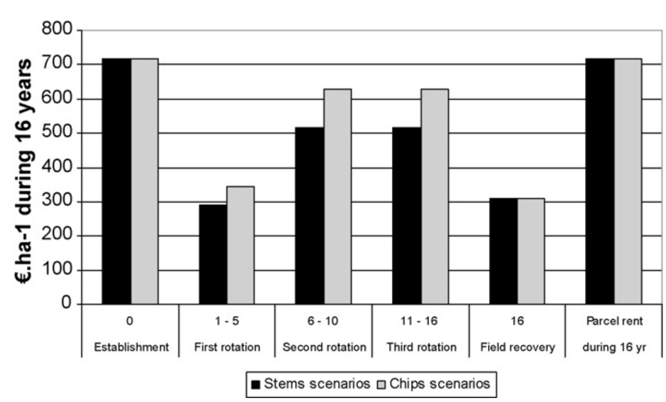

Fig. 3. Contribution of the agricultural labours to total biomass cost production.

Table 10
Total biomass transport cost to the biomass power plant

Scenario	Transport depreciation (10^3 €/yr)	Operating costs		Maintenance costs (10^3 €/yr)	Total (10^3 €/yr)
		Labour cost (10^3 €/yr)	Diesel fuel cost (10^3 €/yr)		
Stems					
Sc. 1	42	77	10	21	150
Sc. 2	56	84	31	23	193
Sc. 3	112	171	34	46	349
Sc. 4	112	209	102	56	479
Sc. 5	196	352	87	95	730
Sc. 6	210	391	260	105	966
Chips					
Sc. 7	70	51	49	31	201
Sc. 8	90	67	146	41	343
Sc. 9	140	113	162	69	484
Sc. 10	190	149	486	91	916
Sc. 11	340	278	413	170	1201
Sc. 12	430	353	1239	215	2237

3.2. Transportation cost

Results in Table 10 show that chip transportation cost are, in certain cases, 65% higher than stem transportation cost for the same quantity of biomass supply (in terms of energy values).

For stem transportation, labour cost is the most expensive factor in the final transportation cost. This represents from 40 to 50% of total transportation cost.

On the other hand, depreciation is the most expensive factor in the final chip transportation cost, representing from 20 to 30% of total transportation cost.

The final biomass cost related to transport mainly depends on the truck driver labour cost and diesel costs when the distances involved are important. The results obtained allow us to assume that a truck depreciation variation will not notably affect biomass transportation cost.

3.3. Final biomass cost

Biomass production, transportation and chipping costs (for stems only) are aggregated, giving the final biomass cost up to the biomass power plant [€ Mg^{-1} (d.b.)] (Table 11).

Chip costs at plant were calculated to be from 18.65 to 23.96 € Mg^{-1}, thus attaining higher costs than for stems transported and chipped at the plant, where the final biomass cost calculated varies from 19.79 to 21.09 € Mg^{-1}.

Comparing the results of final biomass cost obtained with others studies, we observe that SRC crops such as poplar or willow have a similar final cost in a local or regional scenario. In the case of this comparative study [29], the supply cost of stems and chips had a range of 17.6–26.1 € Mg^{-1} dry matter.

3.4. Economic results of biomass power plants

Table 12 shows the economic results for biomass power plants defined in each scenario.

As biomass cost is the factor contributing most to total plant cost, excepting 10 MW power plants, depreciation weight decreases as power plant size increases.

Net present values calculated vary from 27.7 to 28.9 million € for 10 MW power plants, from 95.5 to 99.1 million € for

Table 11
Biomass fuel cost at plant

Scenario	Biomass production and harvesting cost (€ Mg^{-1} biomass)	Transportation cost (€ Mg^{-1} biomass)	Chipping cost (€ Mg^{-1} biomass)	Total cost (€ Mg^{-1} biomass chips)
Stems				
Sc. 1	14.59	2.37	2.83	19.79
Sc. 2	14.59	3.05	2.83	20.48
Sc. 3	14.59	2.47	2.83	19.89
Sc. 4	14.59	3.39	2.83	20.82
Sc. 5	14.59	2.77	2.83	20.19
Sc. 6	14.59	3.66	2.83	21.09
Chips				
Sc. 7	15.48	3.17	–	18.65
Sc. 8	15.48	5.43	–	20.91
Sc. 9	15.48	3.43	–	18.91
Sc. 10	15.48	6.48	–	21.96
Sc. 11	15.48	4.55	–	20.03
Sc. 12	15.48	8.48	–	23.96

Table 12
Economical study of biomass power plants presented as scenarios

Item	Units (×1000)	Scenario											
		Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5	Sc. 6	Sc. 7	Sc. 8	Sc. 9	Sc. 10	Sc. 11	Sc. 12
Capital cost	€	26470		50530		82390		26470		50530		82390	
Depreciation	€ yr^{-1}	1320		2520		4120		1320		2520		4120	
O&M cost													
Biomass cost	€ yr^{-1}	1250	1300	2810	2940	5320	5560	1180	1320	2670	3100	5280	6320
Operating labour	€ yr^{-1}	210		310		490		210		310		490	
Maintenance cost	€ yr^{-1}	400		760		1240		400		760		1240	
Total O + M costs	€ yr^{-1}	1860	1910	3880	4010	7050	7390	1790	1930	3740	4170	7010	8050
Other costs													
Ash disposal cost	€ yr^{-1}	350		770		1420		350		770		1420	
Insurance and others	€ yr^{-1}	260		500		820		260		500		820	
Total other costs	€ yr^{-1}	610		1270		2240		610		1270		2240	
Total plant cost	€ yr^{-1}	3790	3840	7670	7800	13410	13650	3720	3860	7530	7960	13370	14410
Income from energy production	€ yr^{-1}	9970		24920		51600		9970		24920		51600	
Gross profit	€ yr^{-1}	6180	6130	17250	17120	38190	37950	6250	6110	17390	16960	38230	37190
Net profit	€ yr^{-1}	3160	3130	9570	9490	22150	21990	3200	3110	9670	9390	22170	21500
Cash Flow	€ yr^{-1}	4480	4450	12090	12010	26270	26110	4520	4430	12190	11910	26290	25620
Simple payback period (SPP)	Years	5.9	5.9	4.2	4.2	3.1	3.2	5.9	6.0	4.1	4.2	3.1	3.2
Net present value (NPV)	Million €	28.3	28.0	97.8	96.8	240.5	238.5	28.9	27.7	99.1	95.5	240.8	232.3
Internal rate of return (IRR)	%	15.8	15.7	23.4	23.3	31.7	31.5	16.0	15.6	23.6	23.0	31.7	30.9

25 MW and from 232.3 to 240.8 million € for 50 MW power plants. For all the scenarios under study, SPP are less than 6 years, achieving values of 3 years for 50 MW power plants. IRR calculated for 10 MW power plants is higher than 15.6%; for 25 MW, IRR is higher than 23.0% and for 50 MW, IRR exceeds the value of 30.9%.

3.5. Sensibility analysis about plant investment

Results presented in Table 13 shows cash flow and NPV variations for all the scenarios when invested capital cost varies 10% from the initial value selected in the study.

The assessment carried out demonstrates that a fluctuation of 10% in plant investment implies a variation of NPV from 4.73 to 11.40% for 10 MW plants, from 1.56 to 6.25% for 25 MW plants and from 0.29 to 4.32% in the case of 50 MW plants.

3.6. Benefits by selling CO_2 credits

Additional gross benefits for plants attained through selling CO_2 emission credits can substantially increase economic reliability in all cases (Table 14).

According to the values shown in Table 14, for 10 MW plants, an increase from 9.1 to 190% of NPV is attained when the price of CO_2 varies from 5 to 100 € Mg $CO_2{}^{-1}$, respectively. For 25 and 50 MW plants, this range varies from 6.9 to 137%, and 5.8 to 116% for the same CO_2 price deviation, respectively.

3.7. Poplar production variation

Average poplar production yields can vary yearly, thus influencing the final cost of biomass produced on the crop.

Table 13
Sensibility analysis modifying investment value into a range of 10%

Scenario	Capital cost (thousand € yr^{-1})	Depreciation (thousand € yr^{-1})	Cash flow (thousand € yr^{-1})	Net present value (million €)
Sc. 1	23820–29120	1190–1450	4520–4600	26.9–31.5
Sc. 2			4490–4570	26.5–31.1
Sc. 3	45480–55580	2270–2770	12170–12440	96.3–103.9
Sc. 4			12090–12350	95.2–102.9
Sc. 5	74150–90630	3710–4530	26390–27000	239.7–250.3
Sc. 6			26230–26840	237.3–248.3
Sc. 7	23820–29120	1190–1450	4560–4650	27.5–32.0
Sc. 8			4470–4560	26.3–30.9
Sc. 9	45480–55580	2270–2770	12260–12530	97.5–105.1
Sc. 10			11980–12250	93.9–101.5
Sc. 11	74150–90630	3710–4530	26410–27030	240.1–250.6
Sc. 12			25740–26350	231.5–242.0

Table 14
NPV (million €) obtained by selling CO_2 credits at determined CO_2 Mg prices

Power (MW)	Scenario	Million € Mg^{-1} CO_2					
		0	5	10	20	50	100
10	Sc. 1	28.3	31.0	33.7	39.0	55.1	81.8
	Sc. 2	28.0	30.5	33.3	38.5	54.7	81.4
	Sc. 7	28.9	31.5	34.3	39.5	55.6	82.3
	Sc. 8	27.7	30.4	33.2	38.4	54.4	81.2
25	Sc. 3	97.8	104.6	111.3	124.6	164.8	231.5
	Sc. 4	96.8	103.5	110.2	123.5	163.7	230.5
	Sc. 9	99.1	105.7	112.4	125.7	165.9	232.7
	Sc. 10	95.5	102.2	108.8	122.3	162.4	229.1
50	Sc. 5	240.5	254.3	268.2	295.8	378.8	517.2
	Sc. 6	238.5	252.3	266.1	293.9	376.9	515.3
	Sc. 11	240.8	254.7	268.4	296.2	379.2	517.6
	Sc. 12	232.3	246.0	259.9	287.5	370.5	508.9

Table 15
Biomass final cost according to poplar production yield variation in the cultivation, and power plant economical reliability

Concept	Units	10 MW				25 MW				50 MW			
		Sc. 1	Sc. 2	Sc. 7	Sc. 8	Sc. 3	Sc. 4	Sc. 9	Sc. 10	Sc. 5	Sc. 6	Sc. 11	Sc. 12
9 Mg ha^{-1}													
BC at plant	€ Mg^{-1}	27.12	28.08	26.56	29.94	27.50	28.27	27.67	31.22	27.56	28.95	28.13	33.71
Cash flow	10^6 €	4.20	4.10	4.20	4.10	11.40	11.30	11.40	11.00	25.00	26.80	24.90	23.90
NPV	10^6 €	24.40	23.90	24.80	23.00	89.00	88.10	88.80	84.60	224.4	221.3	223.1	210.9
15 Mg ha^{-1}													
BC at plant	€ Mg^{-1}	18.32	18.99	17.06	19.24	18.42	19.32	17.30	20.98	18.71	19.58	18.41	22.17
Cash flow	10^6 €	4.50	4.50	4.60	4.50	12.20	12.10	12.30	12.00	26.50	26.40	26.60	25.90
NPV	10^6 €	29.10	28.70	29.70	28.60	99.60	98.60	100.9	96.70	243.7	241.1	244.4	236.1
20 Mg ha^{-1}													
BC at plant	€ Mg^{-1}	15.02	15.65	13.48	15.46	15.11	15.76	13.67	17.06	15.18	16.17	14.02	18.09
Cash flow	10^6 €	4.70	4.60	4.70	4.60	12.50	12.50	12.70	12.30	27.10	26.90	27.30	26.60
NPV	10^6 €	30.80	30.5	31.70	30.50	103.5	102.7	105.2	101.2	251.4	249.2	253.9	245.0

From this premise, an economic analysis was carried out to determine feasibility in electrical production from poplar production variation in cultivation from 9 to 20 Mg (d.b.) per hectare (Table 15).

For all power plants analysed, the final biomass cost variation with respect to the costs obtained assuming the average production yield mentioned above sees an average increase of 39.8% when production yield decreases to 9 Mg ha^{-1}; this decreases at an average rate of 7.4% when production yield increases to 15 Mg ha^{-1} and decreases by 25.2% when production yield increases to 20 Mg ha^{-1}.

As regards NPV, when biomass yield production decreases to 9 Mg ha^{-1}, the value of this economic indicator decreases by an average of 10.8% for all analysed scenarios. When biomass yield production reaches 15 Mg ha^{-1}, NPV increases by an average of 1.9%; and finally, when the production obtained is 20 Mg ha^{-1}, NPV also increases, to 6.8%.

4. Conclusions

The main conclusion of this study is that biomass power plant implementation is an economically viable option in a regional or local scenario. This study complements others that consider the positive environmental and energetic reliability of the use of poplar as biofuel for energy production. Economic feasibility can be supported if the new benefits of selling CO_2 emissions are added.

The new electrical tariffs (established in Spanish legislation via Royal Decree 611/2007) paying 14.659 c€ kWh produced^{-1}using biomass energy crops as fuel, help to achieve economic reliability for small and medium biomass power plants.

According to the economic results, costs of the cultivation subsystem are the main contributor to the final cost of biomass at plant (72–75% for chip production at plant). Stem or chip production at the harvesting stage must be a logistical decision depending on similar final biomass cost at plant. This variation in final cost reaches a maximum of 2.87 € Mg^{-1} for the same power size.

Stem transportation over the period of a year is made by fewer trucks than in chip transportation. Important drawbacks to be taken into account are truck availability for chip transportation and biomass storage volume needed by the power plant in order to guarantee a water content reduction in biomass during non-harvesting periods.

Loss of water produced by stems in the field optimises the number of kilometres travelled by trucks. As a consequence, chip transportation costs are higher than stems transportation costs, due to the following factors:

- Chip density is lower than for stems.
- Chips are transported with more water content, so more trips are required to transport the same biomass energy (d.b.) to the power plant.
- A greater number of trips per day implies higher transportation depreciation and maintenance costs, and an increase in diesel consumption and labour costs.

In contrast, the effect of crop distribution on the territory does not represent a great disadvantage for final biomass cost, although diesel fuel costs are trebled in all scenarios where the crop distribution area varies from 10 to 90%. When biomass fuel availability is guaranteed at local and regional scales, this study has demonstrated that larger power plants become more economically feasible than small power plants.

The sensibility assessment carried out allows us to observe that the power size of a given plant is a key variable when considering the possible cost fluctuations in the final biomass cost and in the adjustment of plant investment. This fact is attributable to a lower energy auto-consumption and greater energy conversion efficiency by larger biomass power plants. The benefits obtained by selling CO_2 credits have shown themselves to be an important tool in fostering the economic reliability of all biomass plants in comparison with non-renewable power generation systems.

However, the implementation of biomass energy systems should be based on real biomass production potential in the territory and within the infrastructural characteristics facilitating the system's overall logistics.

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